



The dark universe: Primordial black hole \rightleftharpoons dark graviton gas connection

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ABSTRACT

We study the possible correspondence between 5-dimensional primordial black holes and massive 5-dimensional KK gravitons as dark matter candidate within the recently proposed dark dimension scenario that addresses the cosmological hierarchy problem. First, we show that in the local universe a population of 5-dimensional black holes with $M_{\text{BH}} \sim 7 \times 10^{13}$ g would be practically indistinguishable from a KK tower of dark gravitons with $m_{\text{DM}} \sim 50$ keV. Second, we connect the mass increase of 5-dimensional black holes and the related temperature decrease with the cooling of the tower of massive spin-2 KK excitations of the graviton. The dark gravitons are produced at a mass $\sim 1 - 50$ GeV and the bulk of their mass shifts down to roughly $1 - 100$ keV today. The cooling of the system proceeds via decay to lighter gravitons without losing much total mass density, resembling the intra-tower decays that characterize the cosmological evolution of the dynamical dark matter framework. We associate the intra-tower decays of the graviton gas with the black hole growth through accretion. We also discuss that the primordial black hole \rightleftharpoons dark graviton gas connection can be nicely explained by the bound state picture of black holes in terms of gravitons.

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There is growing evidence that a vast class of quantum field theories (QFTs), which are totally consistent as low-energy (IR) effective theories, do not have consistent UV completions with gravity included. Such QFTs that cannot be embedded into a UV complete quantum gravity theory are said to reside in the Swampland, in contrast to the effective field theories that are low energy limits of string theory and inhabit the Landscape [1]. This sorting of QFTs by their consistency with gravity has become an unexpectedly powerful theoretical tool, offering potential solutions to the problems of fine-tuning [2,3].

To be specific, the distance conjecture points to the emergence of infinite towers of states that become light and imply a breakdown of the QFT in the infinite distance limits in moduli space [4]. Stated in the form of the AdS distance conjecture, it suggests that a small cosmological constant corresponds to an infinite field distance limit in field space and that there should be an infinite tower

of states, whose mass is related to the magnitude of the cosmological constant [5]. The spectacular phenomenological consequences of this assertion in connection with the smallness of the cosmological constant in Planck units ($\Lambda \sim 10^{-122} M_{\text{Pl}}^4$) have then recently led to the proposal of the dark universe scenario [6]. It is precisely in this asymptotic limit where quantum gravity (QG) effects become important at scales much below M_{Pl} and hence QG can have an effect on the IR. Indeed, physics would become strongly coupled to gravity at the species scale M_{UV} , which corresponds to the Planck scale of the higher dimensional theory [7,8].

Specifically for the dark universe, requiring the experimental limits (on deviations from Newton's gravitational inverse-square law [9] and neutron star heating [10]) to be consistent with the theoretical bound from the swampland conjectures leads to the prediction of a single extra mesoscopic dimension (a.k.a. the dark dimension) of length $R_{\perp} \sim \lambda \Lambda^{-1/4}$, with $10^{-1} \lesssim \lambda \lesssim 10^{-4}$ [6]. The dark dimension opens up at the characteristic mass scale of the tower, where physics must be described by an QFT in higher dimensions up to the species scale, $M_{\text{UV}} \sim \lambda^{-1/3} \Lambda^{1/12} M_{\text{Pl}}^{2/3}$.

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This seemingly simple model is behind a very rich phenomenology [6,11–14]. For example, two dark matter (DM) candidates have been proposed: (i) primordial black holes (PBHs) that were born very early in the life of the universe [12], and (ii) the massive spin-2 KK excitations of the graviton in the dark dimension (dubbed the “dark gravitons”) [14]. In this Letter we investigate whether there is a possible connection between these DM candidates. Our investigation is deep-rooted on the fact that, for many purposes, a black hole can be replaced by a bound state of gravitons [15].¹

For both scenarios, we consider the canonical picture featuring D-brane-localized fields of the Standard Model (SM) with only gravity propagating in the 5-dimensional bulk [16]. Let us first recall some of the basic features of the 5-dimensional PBHs scenario for dark matter, as introduced in [12]. The radius of a $(4+n)$ -dimensional Schwarzschild black hole is given as

$$r_s(M_{\text{BH}}) = \frac{1}{M_{\text{Pl},n}} \left[\frac{M_{\text{BH}}}{M_{\text{Pl},n}} \frac{2^n \pi^{(n-3)/2} \Gamma(\frac{n+3}{2})}{n+2} \right]^{1/(1+n)}, \quad (1)$$

with the $(4+n)$ Planck mass

$$M_{\text{Pl},n} = \left(\frac{R_{\perp}^{-n} M_{\text{Pl}}^2}{8\pi} \right)^{1/(n+2)}, \quad (2)$$

where R_{\perp} is the radius of the extra dimensional compact space, and where $\Gamma(x)$ is the Gamma function [17]. The transition between a 4-dimensional black hole and a $(4+n)$ -dimensional occurs when $r_s(M_{\text{BH}}) < R_{\perp}$, and this transition occurs independent from n at black hole masses $M_{\text{BH}} < R_{\perp} M_{\text{Pl}}^2$. Note that at the transition point the four-dimensional Schwarzschild radius agrees with the higher dimensional one. As observed in [12], for $R_{\perp} \simeq \lambda \Lambda^{-1/4}$ and $n=1$ as suggested in the dark universe [6], there is a remarkable coincidence, namely the 4D-5D transition occurs at a black hole mass of about $M_{\text{BH}} \sim 10^{20}$ g, precisely the value, below which primordial black holes are viable all-dark-matter candidates.

PBHs radiate all particle species lighter than or comparable to their temperature T_{BH} . For a higher-dimensional black the Hawking temperature is given as [18]

$$T_{\text{BH}} = \frac{n+1}{4\pi r_s}, \quad (3)$$

and the associated entropy takes the form

$$S = \frac{4\pi M_{\text{BH}} r_s}{n+2}. \quad (4)$$

In Figs. 1 and 2 we show the (logarithmic) scaling of the Schwarzschild radius and T_{BH} with M_{BH} for 4- and 5-dimensional black holes. For $M_{\text{BH}} \sim 10^{20}$ g, the horizon size is equal up to some numerical constants to the compactification radius. As one can see, for a given black hole mass, the five-dimensional horizon is larger than for a four-dimensional black hole, whereas the Hawking temperature is smaller in five dimensions than in four dimensions. As a result the five-dimensional black holes have a longer life time compared to four-dimensions, which makes them viable all-dark-matter candidates.

Let us briefly also recall the main features of the dark gravitons as dark matter candidates, where we refer to [14] for more details. The dark gravitons are produced thermally by the hot brane at $m_{\text{DM}} \sim 4$ GeV. While the total mass of the dark KK gravitons remains approximately constant over time, its mass distribution quickly shifts to lower values by the large number of available KK modes of lighter mass, thereby preventing DM from substantially

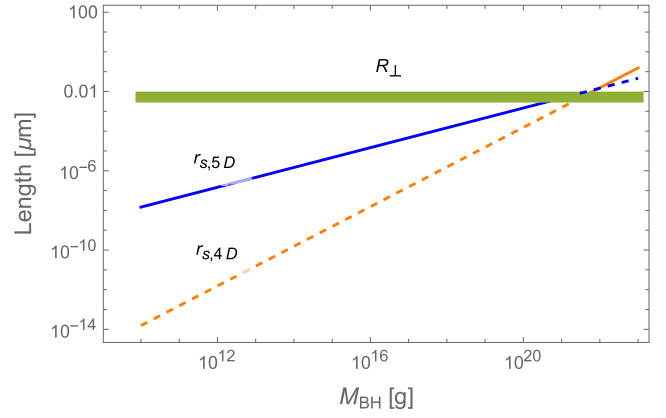


Fig. 1. Scaling of the Schwarzschild radius with M_{BH} for 4- and 5-dimensional black holes. The thick horizontal line indicates the size of the compactification radius.

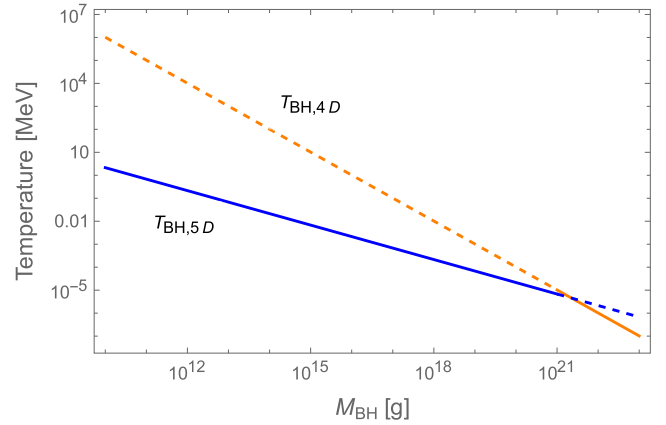


Fig. 2. Scaling of T_{BH} with M_{BH} for 4- and 5-dimensional black holes.

decaying back to SM fields. The dark graviton model then provides a particular realization of the dynamical dark matter (DDM) framework [19], with dominance of intra-tower decays and a small decay rate ($\propto m_{\text{DM}}^3$) to the SM fields. Consistency with experimental data requires that the DM mass from the time of matter-radiation (MR) equality till today decreases from $m_{\text{DM}}(\text{MR}) \sim 1$ MeV to $m_{\text{DM}}(\text{today}) \sim 50$ keV [14].

Before proceeding, we pause to review experimental constraints on these dark matter candidates. PBH dark matter has been challenged by many observational probes that set bounds on the relative PBH abundance across a broad range of viable PBH masses [20]. Among these bounds, those coming from microlensing gravitational surveys yield the most restrictive constraints for $M_{\text{BH}} \gtrsim 10^{22}$ g [21]. An astonishing coincidence is that the size of the dark dimension $R_{\perp} \sim$ wavelength of visible light. This means that the Schwarzschild radius of 5D black holes is well below the wavelength of light. For point-like lenses, this is the critical length where geometric optics breaks down and the effects of wave optics suppress the magnification, obstructing the sensitivity to 5D PBH microlensing signals. In principle, femtolensing of cosmological gamma-ray bursts (GRBs) could be used to search for dark matter objects in the mass range $10^{17} \lesssim M_{\text{BH}}/\text{g} \lesssim 10^{20}$ [22]. The lack of femtolensing detection by the *Fermi* Gamma-ray Burst Monitor was used to constrain PBHs with mass in the range $10^{17.7} < M_{\text{BH}}/\text{g} \lesssim 10^{20}$ to contribute no more than 10% to the total dark matter abundance [23]. However, the validity of this GRB constraint has been called into question, because it is based on the assumption that the gamma-ray source is point-like in the lens plane [24]. The non-pointlike nature of GRBs imply that most

¹ This possible connection was already mentioned in [14].

of them are too big when projected onto the lens plane to yield meaningful femtolensing limits. Indeed, only a small GRB population with very fast variability might be suitable for PBH searches. When this systematic effect is taken into account to decontaminate the *Fermi* sample, the GRB constraint on PBHs becomes obsolete. A sample of 100 GRBs with transverse size 10^9 cm would be needed to probe the 5D PBHs [24]. Should a positive signal be detected, it can be used as a discriminator between the PBH and dark graviton hypotheses.

A combination of temperature and polarization data from *Planck* provides strong constraints on the abundance of dark gravitons and PBHs. On the one hand, the model-independent bound on decaying dark matter derived in [25] constrains the KK mass $\lesssim 1$ MeV at the epoch of matter-radiation equality [14]. On the other hand, *Planck* data combined with observations of the MeV extragalactic gamma-ray background constrain the abundance of PBHs for $M_{\text{BH}} \lesssim 10^{12}$ g.²

Now let us explain the possible microscopic reason for the correspondence between the black holes and the dark gravitons as dark matter candidates. It is based on the description [15], where a black hole can be viewed as being composed, i.e. is a bound state, of N gravitons. The number N then agrees with the entropy of the black hole: $N \simeq S$. So far this picture was used for massless gravitons. But we now apply it to a black hole of mass M_{BH} , which is composed of N massive gravitons, each of mass m_{DM} . So we can immediately determine the number N , i.e. the number of massive graviton constituents, as

$$N = \frac{M_{\text{BH}}}{m_{\text{DM}}}. \quad (5)$$

As said, N agrees with the entropy, and we can also express the entropy as the ratio of black mass and temperature, i.e.

$$N \simeq S \simeq \frac{M_{\text{BH}}}{T_{\text{BH}}}. \quad (6)$$

From that we first deduce that we should associate the graviton constituent mass m_{DM} with the black hole Hawking temperature T_{BH} :

$$m_{\text{DM}} \simeq T_{\text{BH}}. \quad (7)$$

As said, the black hole contains $M_{\text{BH}}/m_{\text{DM}}$ dark gravitons and the total dark matter mass density is the same in both pictures. Furthermore the decay of the higher mass KK dark gravitons to lower mass gravitons corresponds to the accretion of the black hole, i.e. to lowering its temperature by increasing its mass. The black hole entropy also increases by the accretion process, so the number N of dark gravitons also increases accordingly and the overall mass stays the same. This brings us to a second, new interesting proposal for the black hole \rightleftharpoons graviton gas correspondence: *The cooling of the graviton gas can be visualized as the black hole growth by accreting mass from the surrounding plasma.*

This is an interesting association that we now turn to study in detail for the dark universe. Here the Hawking temperature is related to the black hole mass M_{BH} by [12]

$$T_{\text{BH}} = \sqrt{\frac{3}{64}} \frac{1}{\pi} \frac{M_{\text{Pl}} \Lambda^{1/8}}{\lambda^{1/2} M_{\text{BH}}^{1/2}} \approx \left(\frac{M_{\text{BH}}}{5 \times 10^{10} \text{ g}} \right)^{-1/2} \text{ MeV}, \quad (8)$$

where we have taken $\lambda = 10^{-4}$. This radiation causes PBHs to lose mass at a rate

$$\begin{aligned} \left. \frac{dM_{\text{BH}}}{dt} \right|_{\text{evap}} &= - \frac{\Lambda^{1/4} M_{\text{Pl}}^2}{640 \pi \lambda M_{\text{BH}}} \sum_i c_i(T_{\text{BH}}) \tilde{f} \Gamma_s \\ &= -2.7 \times 10^{27} \text{ GeV}^3 \frac{1}{M_{\text{BH}}} \sum_i c_i(T_{\text{BH}}) \tilde{f} \Gamma_s, \end{aligned} \quad (9)$$

where $c_i(T_{\text{BH}})$ counts the number of internal degrees of freedom of particle species i of mass m_i satisfying $m_i \ll T_{\text{BH}}$, $\tilde{f} = 1$ ($\tilde{f} = 7/8$) for bosons (fermions), and where $\Gamma_{s=1/2} \approx 2/3$ and $\Gamma_{s=1} \approx 1/4$ are the (spin-weighted) dimensionless greybody factors normalized to the black hole surface area [12]. We are interested here in $T_{\text{BH}} \lesssim 1 \text{ MeV}$ and so $c_i(T_{\text{BH}})$ receives a contribution of 6 from neutrinos, 4 from electrons, 2 from photons. In the spirit of [27], we neglect graviton emission because the KK modes are excitations in the full transverse space, and so their overlap with the small (higher-dimensional) black holes is suppressed by the geometric factor $(r_s/R_\perp)^2$ relative to the brane fields. Thus, the geometric suppression precisely compensates for the enormous number of modes, and the total contribution of all KK modes is only the same order as that from a single brane field.

Integrating (9) we find that a black hole with an initial mass of $M_{\text{BH}} \sim 2 \times 10^{11}$ g will evaporate in a time equal to the age of the universe (which is taken to be 13.787 ± 0.020 Gyr [29]). The characteristic energy of the emitted particles is 500 keV. A black hole of $M_{\text{BH}} \sim 5 \times 10^{12}$ g radiates particles with an average energy ~ 100 keV and has a lifetime $\sim 7.6 \times 10^{10}$ yr, whereas for $M_{\text{BH}} \sim 7 \times 10^{13}$ g, the average particle energy ~ 25 keV and the black hole lifetime $\sim 1.5 \times 10^{15}$ yr. On the other hand, PBHs of $M_{\text{BH}} \sim 5 \times 10^{10}$ g have a lifetime of 0.5 Gyr and radiate particles with average energy ~ 1 MeV.

In order to compare with the behaviour of the graviton dark matter candidates, we now turn to ascertain whether 5-dimensional PBHs of $T_{\text{BH}}(\text{MR}) \sim 1$ MeV at the MR equality could cool down to $T_{\text{BH}}(\text{today}) \sim 25$ keV and survive until today. The net change of the black hole mass is given by a balance equation

$$\frac{dM_{\text{BH}}}{dt} = \left. \frac{dM_{\text{BH}}}{dt} \right|_{\text{accr}} + \left. \frac{dM_{\text{BH}}}{dt} \right|_{\text{evap}}, \quad (10)$$

where

$$\left. \frac{dM_{\text{BH}}}{dt} \right|_{\text{accr}} \approx \frac{64\pi}{3} \frac{M_{\text{BH}} \lambda}{\Lambda^{1/4} M_{\text{Pl}}^2} \varepsilon, \quad (11)$$

and where ε is the energy density of the plasma in the vicinity of the event horizon [12]. Substituting (9) and (11) into (10), it follows that for accretion to dominate the black hole evaporation,

$$\begin{aligned} \varepsilon &> \frac{1}{40960 \pi^2} \frac{\Lambda^{1/2} M_{\text{Pl}}^4}{\lambda^2 M_{\text{BH}}^2} \sum_i c_i \tilde{f} \Gamma_s \\ &> \frac{2 \times 10^{56}}{M_{\text{BH}}^2} \sum_i c_i \tilde{f} \Gamma_s \text{ GeV}^6. \end{aligned} \quad (12)$$

For $M_{\text{BH}} \sim 5 \times 10^{10}$ g, we find $\varepsilon > 2 \times 10^{-10} \text{ GeV/fm}^3$. Amusingly, for the temperature range of interest ($T_{\text{BH}} \lesssim 1$ MeV) the required ε for black hole stability is well below the energy density of partons formed in lead-lead collisions at LHC: $\varepsilon_{\text{LHC}} \sim 500 \text{ GeV/fm}^3$ [28].

Next, in line with our stated plan, we get an estimate of the average energy density in the primordial plasma by looking at the radiation energy density, which is given by the Stefan-Boltzmann law

$$\langle \varepsilon_{\text{rad}} \rangle = \frac{\pi^2}{30} g_\varepsilon(T) T^4, \quad (13)$$

where $g_\varepsilon(T)$ counts the effective number of relativistic helicity degrees of freedom at a given photon temperature T ; as in (9)

² This mass range has been estimated by a rudimentary rescaling of the bound of derived in [26] for 4D PBHs.

Table 1

History of temperature changes in the early universe [30].

Epoch	Temperature	Age
Electroweak Phase Transition	$T \sim 100 \text{ GeV}$	20 ps
QCD Phase Transition	$T \sim 150 \text{ MeV}$	20 μs
Neutrino Decoupling	$T \sim 1 \text{ MeV}$	1 s
Electron-Positron Annihilation	$T < m_e < 0.5 \text{ MeV}$	10 s
Big Bang Nucleosynthesis	$50 \lesssim T/\text{keV} \lesssim 100$	10 min
Matter-Radiation Equality	$T \sim 0.8 \text{ eV} \sim 9000 \text{ K}$	$6 \times 10^4 \text{ yr}$
Photon Decoupling	$T \sim 0.3 \text{ eV} \sim 3000 \text{ K}$	$3.8 \times 10^5 \text{ yr}$

fermionic degrees of freedom are suppressed by a factor 7/8 with respect to bosonic degrees of freedom. Using the characteristic temperatures for the different epochs of the universe given in Table 1 we find that at MR equality $\langle \varepsilon_{\text{rad}} \rangle \sim 2 \times 10^{-34} \text{ GeV/fm}^3$, whereas at neutrino decoupling $\langle \varepsilon_{\text{rad}} \rangle \sim 5 \times 10^{-10} \text{ GeV/fm}^3$. We conclude that the accretion of the black hole and the cooling down process can generically occur at $T \sim 1 \text{ MeV}$, i.e. at the epoch, where the neutrinos are decoupling. However one can imagine to push down this temperature to the epoch of matter-radiation equality. Since the average density is already much lower at this epoch, it may be possible to cool down a black hole from $T_{\text{BH}}(\text{MR}) \sim 1 \text{ MeV}$ to $T_{\text{BH}}(\text{today}) \sim 25 \text{ keV}$, only if the primordial plasma at matter-radiation equality has fluctuations at the level of ~ 1 in 10^{24} . Whether this is possible, is an open and model dependent question.

In summary, we have discussed the possible correspondence between dark gravitons and primordial black holes as dark matter candidates in the dark universe. Associating the black hole Hawking temperature with the mass of the dark graviton, we have shown that today a population of 5-dimensional PBHs with $M_{\text{BH}} \sim 7 \times 10^{13} \text{ g}$ would be practically indistinguishable from a KK tower of dark gravitons with $m_{\text{DM}} \sim 50 \text{ keV}$. We have shown that up to some numerical factors the radiation rate of 5-dimensional black holes is comparable to the graviton emission into brane-localized SM fields. Although this is not the dominant channel describing the cosmological evolution of the dark universe, it is the one that produces visible signals for observers living on the brane. In other words, from the point of view of the 4-dimensional observers it will be challenging to distinguish among the two DM candidates.

In addition we have investigated the possible correspondence between the mass change rate of 5-dimensional black holes and the cooling of the tower of massive spin-2 KK excitations of the graviton in the dark dimension. The dominant decay channel of the dark graviton gas is into lighter gravitons. This has a correspondence with the black hole accretion process. The dark gravitons are produced at a mass $\sim 1 - 50 \text{ GeV}$ and the bulk of their mass shifts down to roughly $1 - 100 \text{ keV}$ today. The cooling of the system proceeds via decay to lighter gravitons without losing much total mass density, resembling the intra-tower decays characterizing the cosmological evolution of the DDM framework. We interpreted the intra-tower decays of the graviton gas with the black hole growth via accretion of the plasma in the vicinity of its horizon. In principle, with the right amount of energy density on the plasma surrounding the black hole horizon one could make a one-to-one correspondence. However, it happens to be that the cosmic expansion of our universe does not have on average enough energy density for black holes with $T_{\text{BH}} \sim 1 \text{ MeV}$ to overtake the radiation process via accretion at the matter radiation equality. It is around the epoch of neutrino decoupling where the average energy density of the plasma may allow black holes of $T_{\text{BH}} \sim 1 \text{ MeV}$ to survive until today via accretion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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